NEW TECHNIQUES FOR ORBIT DETERMINATION OF GEOSYNCHRONOUS, GEOSYNCHRONOUS-TRANSFER, AND OTHER HIGH-ALTITUDE EARTH ORBITERS

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This paper explores two innovative approaches to high-altitude orbit determination. GPS-enhanced tracking (GET), which has been field-tested by JPL with two geosynchronous satellites, utilizes inexpensive ground terminals developed from commercial GPS receivers. The second approach involves tracking GPS directly onboard, soon to be tested by JPL with a new microGPS receiver, also known as the Bit Grabber GPS Space Receiver (BGGSR), requiring < 0.1 watt power on average. First BGGSR launch is anticipated late summer 1997. A 1998 launch is planned for STRV- 1 C in geosynchronous-transfer orbit to track GPS over a wide altitude range. The paper discusses experimental setup and positioning results from ground and space data analysis for these new techniques.

INTRODUCTION

GPS measurements can support near real-time positioning at the sub-cm level for terrestrial users, and at the few-cm level for low-Earth spaceborne users equipped with high quality GPS receivers when data from a global ground network are available for accurate determination of GPS ephemerides and clocks (Refs. 1-3). For solutions using wide area differential GPS techniques, recent results have shown that real-time terrestrial and airborne accuracies can approach a few tens of centimeters (Ref. 4). Depending on the dynamical information available, certain low-Earth users could even, in principle, achieve better real-time positioning accuracy than mobile ground/airborne users, since exploitation of the dynamical information anti the predictability of a well-behaved orbit could result in further reduction or averaging down of the total error.

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For spaceborne users above low-Earth altitude, however, the visibility of the GPS satellites falls off rather rapidly, as is shown in Figures 1 and **2.** Three techniques are shown in Figure 1: (A) up-looking GPS, which is the conventional terrestrial use, where a GPS receiving antenna is zenith-pointed to track GPS satellites; (B) GPS-enhanced tracking (GET), where a beacon signal from a high-altitude non-GPS space vehicle is tracked along with regular GPS signals in an enhanced GPS receiver (which could be on the ground or in flight); and (C) down-looking GPS, where a GPS receiving antenna is pointed slightly off-nadir to pick up GPS signals from the other side of the Earth. Figure 2 shows the average number of GPS in view for different types of tracking techniques as a function of altitude.

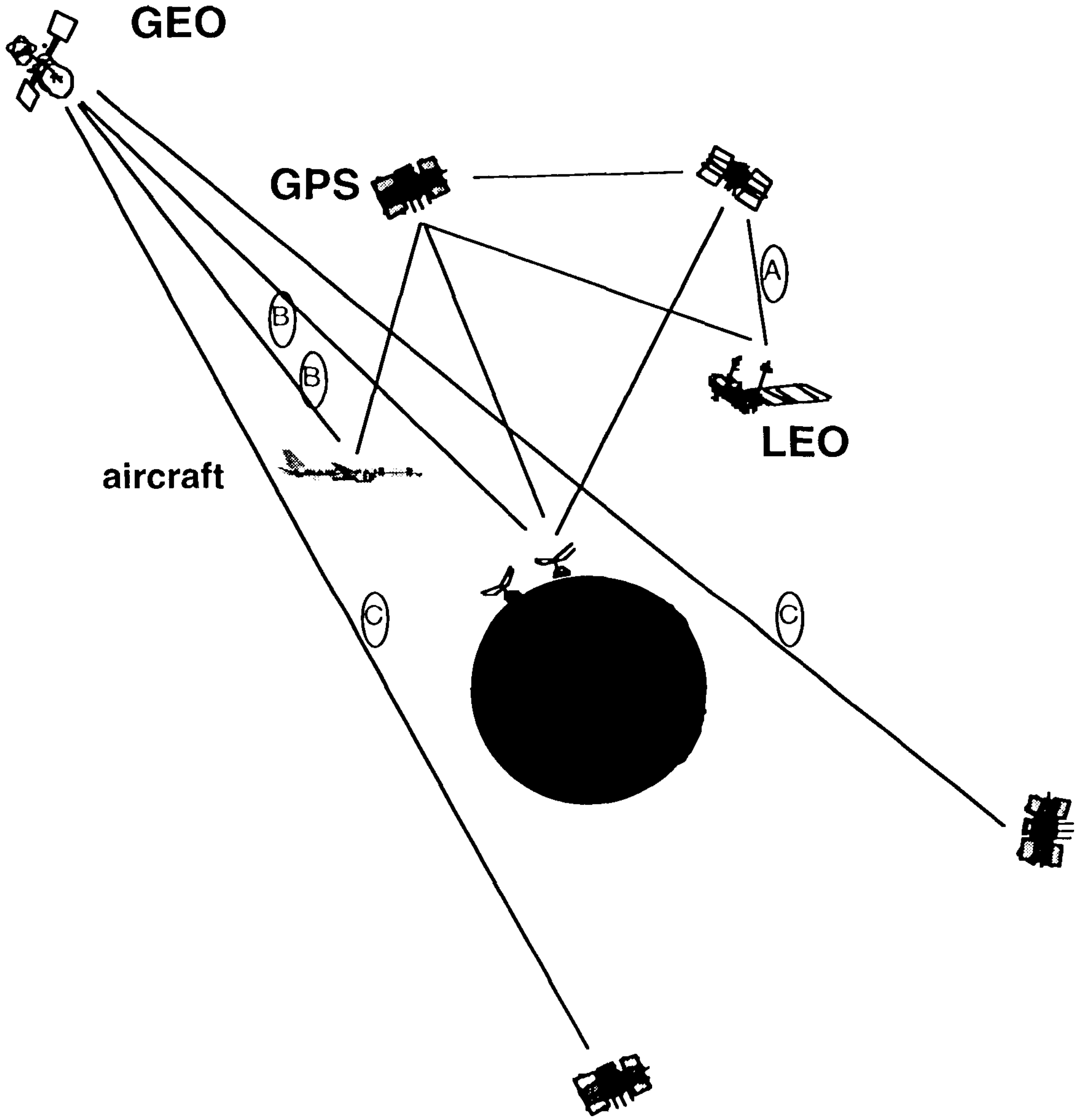


Figure 1 Illustration of three different GPS tracking techniques: (A) Up-looking GPS; (B) GPS-enhanced tracking (GET); and (C) down-looking GPS.

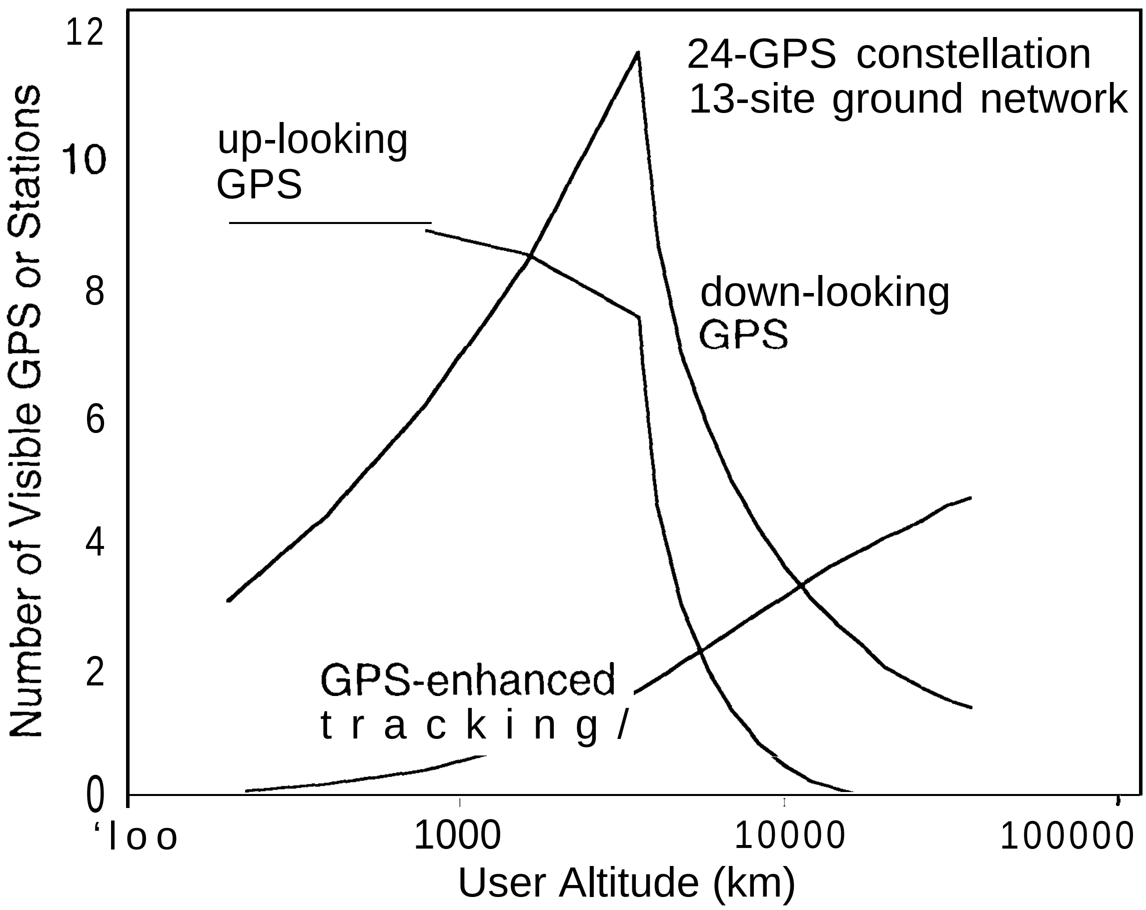


Figure 2 Plot showing number of GPS visible, on average as a function of altitude, for GPS receivers utilized for up-looking and down-looking GPS tracking. Also shown is average number of ground sites simultaneously tracking a beacon from an Earth orbiter with GPS-enhanced tracking, based on a total ground net of 13 sites evenly distributed around the globe.

The Jet Propulsion Laboratory (JPL) has been studying all three of the techniques shown in Figures 1 and 2 for more than ten years. GPS data obtained from up-looking GPS space receivers have been extensively analyzed from several satellites ranging in altitude from 500 km to 1330 km (Refs. 1,2,5,6); in the case of GPS-enhanced tracking, prior to 1994, studies of that technique relied on simulations or covariance studies. In January 1994, JPL successfully performed a field experiment to demonstrate the GET technique for tracking of two TDRS geostationary satellites (Refs. 7,8). However, analysis of real data from a down-looking GPS experiment have not, to our knowledge, been published in the open literature. In early 1999, JPL plans to track GPS satellites from a unique "bit-grabber" GPS space receiver (13 GGSR), also know as microGPS (Refs. 9, 10), on the STRV-1C satellite to be launched by the United Kingdom DERA (Defense and Evaluation Research Agency). Since this satellite will be in an elliptical orbit, it will cover the altitude range from a few hundred km up to geosynchronous altitude. The JPL microGPS receiver will be sampling GPS signals over the entire STRV-1C altitude range (most of the range shown in Figure 2).

Up-looking GPS tracking (Figures 1, 2) is effective primarily at altitudes below 2000 km. because of the relatively narrow GPS transmit beam. In counting GPS for visibility, Figures 1 and 2 assume that beyond 22 degrees from the GPS boresight, no GPS can be tracked. This is somewhat of an oversimplification: Block 11A (current) antenna L I gain is down 3 dB from peak at 17 degrees off boresight, with peak gain at 10 degrees; Block II antenna L2 gain is down 3 dB from peak at 20 degrees off boresight, with peak gain at 12 degrees; Block IIR (current) antenna L l gain is down 3 dB from peak at 15 degrees off boresight, with peak gain at 9 degrees. Note that the trend is for the GPS broadcast beam to narrow in the future. It might be possible to increase the effective number of visible GPS for the high altitude cases (Figure 2) by assuming that GPS data could be tracked from the sidelobes of the broadcast beam. This could increase the number of satellites in view from a geostationary satellite (down-looking GPS) to 3-4 or even more, as discussed below. This would lead to an improvement in the geostationary positioning errors which are discussed later in this paper.

In this paper, we review the relative capabilities for positioning from up-looking GPS, GET, and down-looking GPS, and discuss the upcoming microGPS experiment on the STRV- 1 C mission.

NEAR-EARTH GPS TRACKING: UP-LOOKING GPS

Figure 3 summarizes a wide range of positioning capabilities for low-Earth and near-Earth accuracies for non-stationary GPS users. Not shown in Figure 3 is the user positioning accuracy for a stationary ground receiver: recent averages for over 100 ground site solutions at JPL around the world show daily rms accuracies of 5 mm in the horizontal and better than 10 mm in the vertical. Most of the data in Figure 3 are based on results which have been achieved at JPL with real data. Figure 3 includes recent results from wide area differential GPS (WADGPS) analysis. WADGPS involves real-time computation of precise corrections to the GPS broadcast ephemerides from analysis of ground network data— including orbital, space vehicle clock, selective availability, and ionosphere delay corrections — which are used to provide users with real-time positioning accuracy as much as two orders of magnitude better than would be available without the WADGPS corrections. Case 1 also requires analysis of GPS ground data from a network.

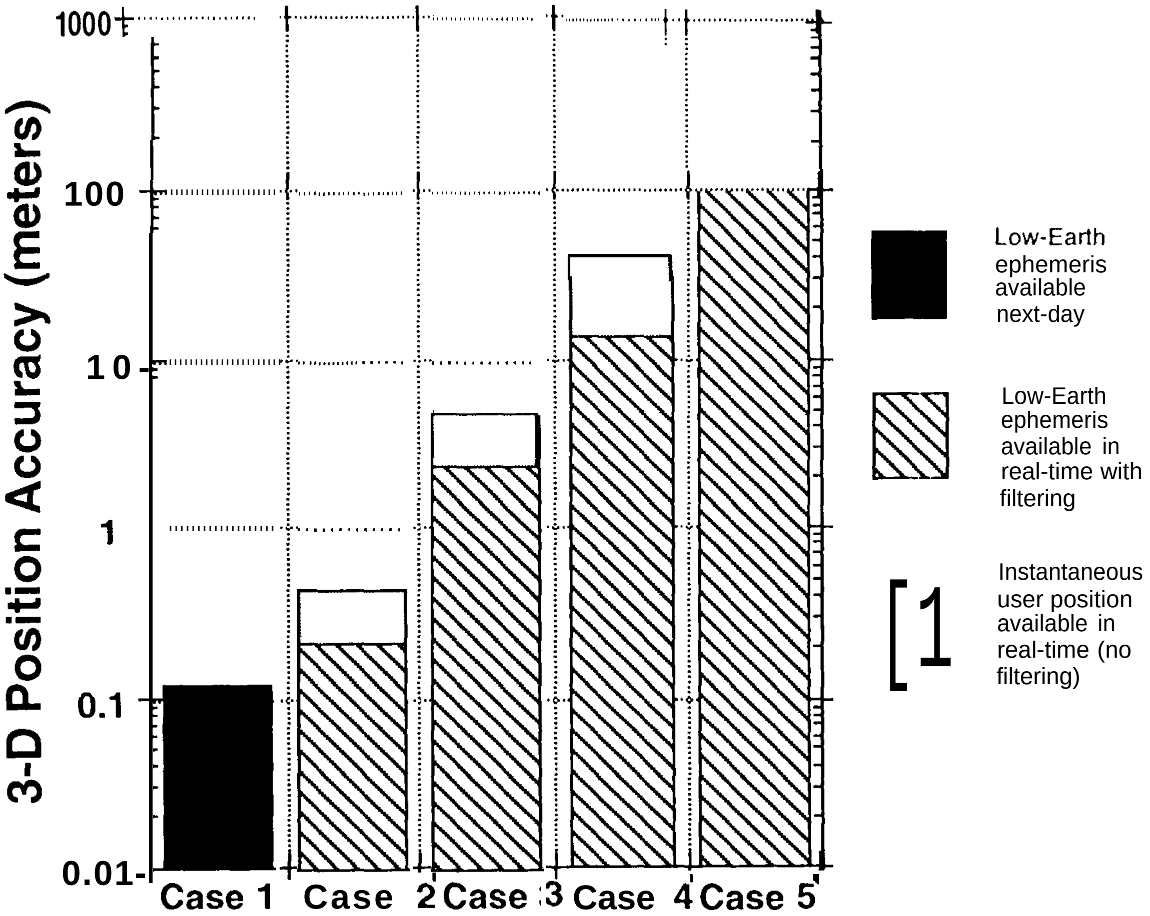


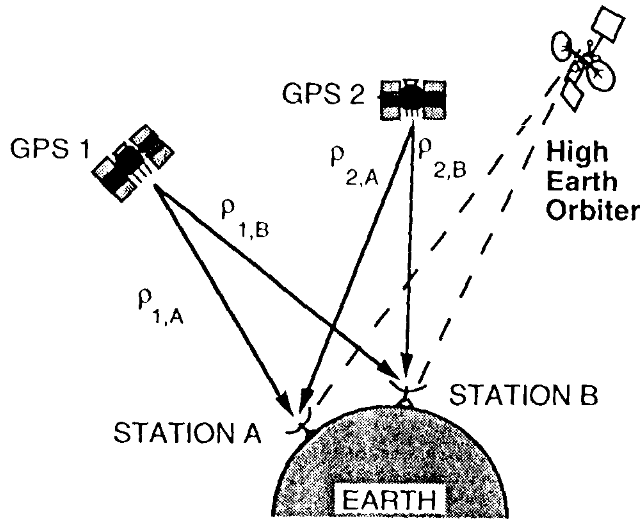
Figure 3 Real-time and post-fit accuracies for non-stationary up-looking GPS users. Case 1 shows post-fit results achieved at JPL for the Topex/Poseidon satellite at 1330 km altitude (Ref. 1). Case 2 shows recent instantaneous real-time WADGPS positioning results achieved at JPL (Ref. 4) and anticipated filtered real-time WADGPS capability for a Topex-like orbiter. Case 3 shows performance for real-time Y-code authorized GPS users without WADGPS. Case 4 shows accuracy for low-Earth orbiter solutions for users with 1.1-CA only receivers, both instantaneous and filtered solutions. Case S is for a low-Earth orbiter carrying a microGPS receiver, which samples GPS signals only intermittently.

HIGH-ALTITUDE GPS TRACKING

At altitudes above about 2000 km (Figure 2), the visibility of GPS signals drops off rapidly. For higher altitudes, a different approach must be used for GPS-based positioning. In this paper, we discuss two such approaches: GPS-enhanced tracking, and down-looking GPS. GPS-enhanced tracking refers to a novel usc of GPS ground receivers to simultaneously track both GPS satellites as well as the non-GPS satellites of interest. Although the non-GPS satellites can be at essentially any altitude, of particular interest here is the case of a geosynchronous satellite, or a satellite in geosynchronous transfer (elliptical) orbit.

GPS-Enhanced 'Tracking (GET)

The GET concept is based in part on the success which has been achieved in precise orbit determination for GPS satellites from ground-based tracking. The expectation is that if a beacon signal from a high-Earth satellite were GPS-like or GPS-compatible, it could be tracked in GPS ground receivers along with GPS satellites and, for a reasonable beacon signal structure, the orbit of the high-Earth satellite could be determined relative to the reference frame in which the GPS orbits are estimated to high accuracy.



range

range (phase) bias

clock offsets

$$\Phi_{1,A} = [\rho_{1,A} + B_{1,A} + C_1 + C_A]\, 2\pi/\lambda$$
$$\Phi_{1,B} = [\rho_{1,B} + B_{1,B} + C_1 + C_A]\, 2\pi/\lambda$$
$$\Phi_{2,A} = [\rho_{2,A} + B_{2,A} + C_2 + C^{B}_{A}]\, 2\pi/\lambda$$
$$\Phi_{2,B} = [\rho_{2,B} + B_{2,6} + C_2 + C_B]\, 2\pi/\lambda$$

$$(\Phi_{1,B} - \Phi_{1,A}) - (\Phi_{2,B} - \Phi_{2,A})$$
$$= [(\rho_{1,6} - \rho_{1,A}) - (\rho_{2,B} - \rho_{2,A}) + B]\, 2\pi/\lambda$$

Figure 4 Differential GPS-enhanced tracking. Simultaneous measurements of carrier phase (Φ) enable removal of transmitter and receiver clock offsets. After tracking for ~ 24 hrs, the resultant linear combination of ranges enables estimation of GPS orbits to -10-15 cm, and of ground coordinates to sub-cm accuracy. The term B, in the final equation, is a composite bias term which is easily estimated from -3 hrs of tracking. In G1'S-enhanced tracking, the carrier phase from the high-Earth orbiter would also be included and its orbit similarly estimated.

Figure 4 shows Schematically how GET relates to differential GPS tracking. This relationship is discussed at length in Ref. 7, While GPS orbits arc routinely produced at JPL to better than 15 cm accuracy (D. Jefferson [J PL], private communication), the expectation is that the accuracy for a high-Earth or geosynchronous satellite would be somewhat worse than what can be achieved for actual GPS satellites because of degraded geometry

In practice, it is unreasonable to assume that geosynchronous orbiters can be equipped with actual GPS transmitters. Our interest here lies in how the GET method can be adapted to function with assorted satellite transmissions, and to satisfy varied orbit determination requirements for existing and future geosynchronous orbiters. In this context, we summarize results from a recent experiment in which the GET method was adapted to track spacecraft from the Tracking and Data Relay Satellite (TDRS) geosynchronous constellation. For a complete description of the TDRS experiment, see Refs. 7 and 8.

A short ground baseline tracking scenario for TDRS is necessitated by the nature of the existing space-to-ground link (SGL). The TDRS SGLS illuminate only a limited area of the southwestern U.S. surrounding the TDRS Earth station at White Sands, New Mexico (Figure 5), precluding the use of globally dispersed stations for tracking the SGL. However, if a GET network fitting within the SGL footprints could be designed to deliver the desired accuracy, significant benefits could be gained: 1) The SGL is always on when the TDRS is servicing users. Thus the signal can be passively monitored and no TDRS services need be scheduled for orbit determination. 2) The SGL is broadcast at Ku-band (1 3.731 GHz). At this frequency, the delay caused by the presence of charged particles along the signal path (i.e., ionosphere delay) rarely exceeds a few cm in equivalent range. 3) A small ground network in the vicinity of the White Sands complex (WSC) has many operational advantages: all the sites can be readily accessed for maintenance, and communications links to the Earth station can be made” reliable and short.

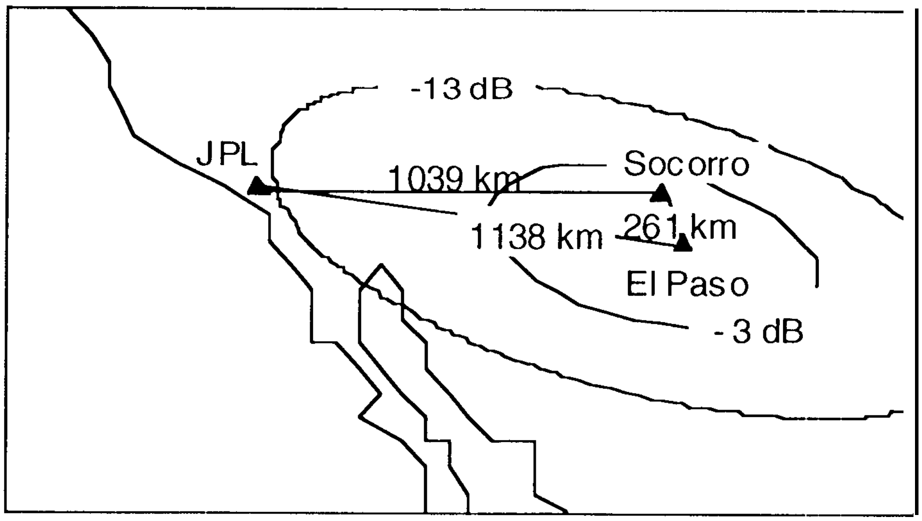


Figure 5. Configuration of TDRS/GPS tracking network. The footprint of the TDRS-3 space-to-ground link (SGL) during the Jan. 1994 experiment is shown.

Coincident observation of GPS and TDRS signals in the same ground receiver enables calibrations of clock errors and tropospheric delays. An added benefit is the ability of GPS to provide very precisely (sub cm) the positions of the tracking stations relative to one another, and the network orientation in the terrestrial reference frame. Each modified GPS receiver tracks the phase of the TDRS SGL with great precision (enabled by GPS). Contained in the station-differenced phase data is very precise information on the velocity of the TDRS spacecraft in the plane of the sky. Using the information in a standard dynamical orbit determination strategy determines very precisely five of the six osculating (classical) elements that describe the geosynchronous TDRS orbit. In order to determine the last component-the longitude of the satellite orbit or, for TDRS in geostationary orbit, its along-track position in inertial space-some knowledge of the range to the spacecraft is needed. To provide this information, we used a very small sample of data from routine ranging done at WSC.

JPL performed the TDRS/GPS tracking demonstration January 16-22, 1994. GPS and TDRS satellites were tracked simultaneously from three sites: El Paso, TX, Socorro, NM, and Pasadena, CA (Figure 5). This configuration permitted us to test the performance of side-lobe tracking, as JPL is in a fortuitous location that placed it in the first side lobe of the SGLS from both TDRS-5 (175° W) and TDRS-3 (62° W). The other two stations, operated from motel rooms in El Paso and Socorro, were within the main beam of the SGL of both TDRS-3 and 5. At each tracking station was an enhanced TurboRogue GPS receiver. The TurboRogue, originally developed at JPL and currently globally distributed in a 60+ receiver network used for precise GPS orbit determination and a variety of geodetic and tectonic investigations, was augmented for this experiment with a small, Ku-band horn antenna (opening dimensions 17 X 14 cm) and a Ku- to L-band downconverter (Figure 6). In addition, the TurboRogue software was modified to measure and record the phase of the TDRS SGL with the same sub-mm precision and receiver time-stamp as GPS carrier phase measurements. This system architecture produces data products that significantly simplify subsequent orbit determination processing.

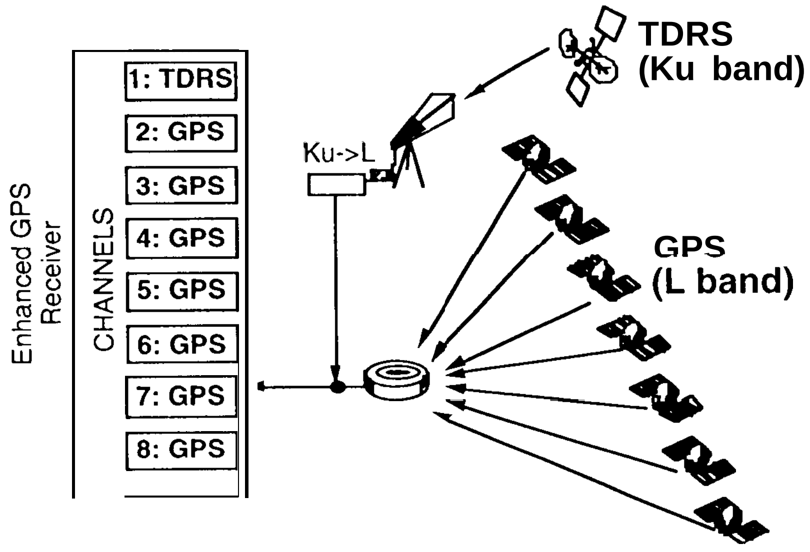


Figure 6. Schematic for the GPS ground receiver enhanced to simultaneously track TDRS along with GPS satellites.

Two of the TDRS-3 orbit solutions overlap by -4 hr (Figure 7). The RMS differences of the two solutions during the overlap is 2, 1 I, and 11 m in height, cross track and along track respectively. A better measure of the orbit accuracy is gained from external comparisons. To this end, we compared our TDRS orbit solutions (in an inertial J2000 frame) against the NASA's operational Bilateral Ranging Transponder System (BRTS) orbits from Goddard Space Flight Center (GSFC), typically accurate to 50 m in total position (1-0).

Figure 8 summarizes the differences with respect to the BRTS orbits for all four solutions. The RMS differences range from 1 to 7 m in height, 13 to 26 m cross track, and 14 to 31 m along track. Especially encouraging are the results for TDRS-5, which was tracked at a very low elevation (100). Moreover, the signature that TDRS-5 traced in the "plane of sky was very compact compared to the one for TDRS-3. Despite these important differences, the TDRS-5 orbit accuracy appears only slightly degraded.

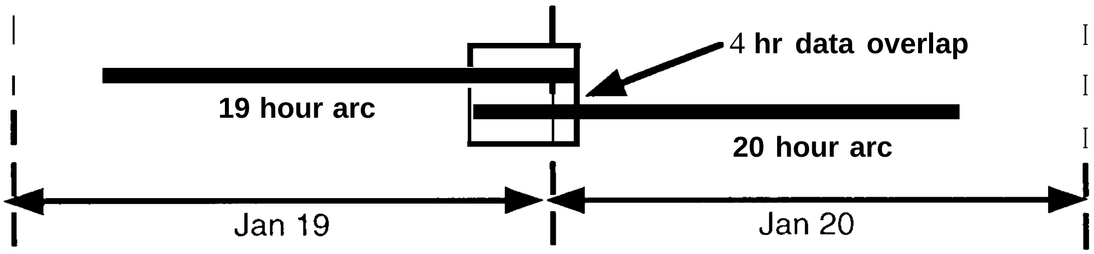


Figure 7. Schematic of orbit overlap for TDRS-3 orbit comparison.

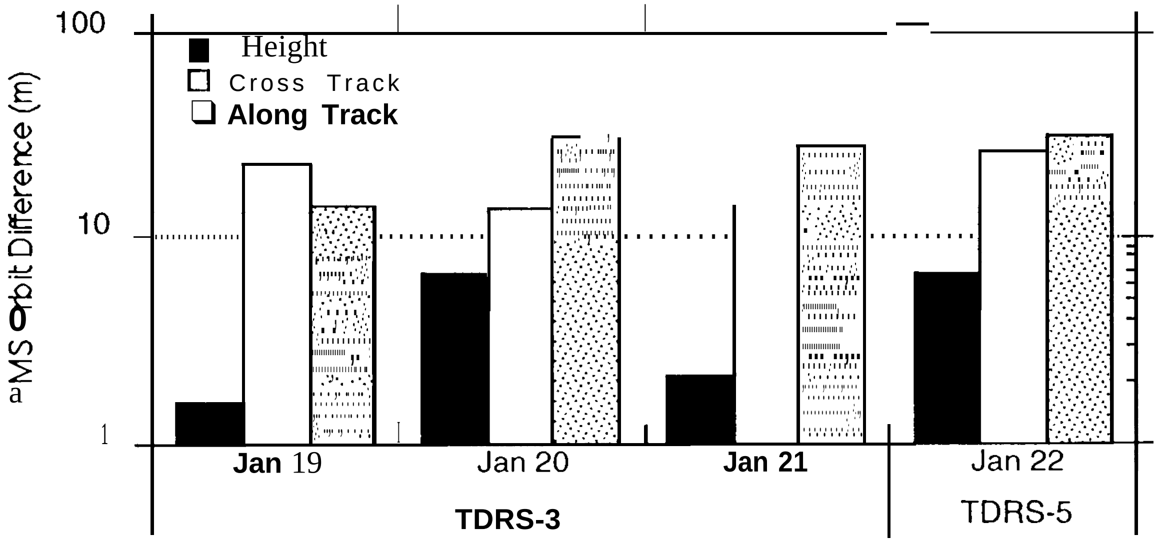


Figure 8. Bar graph summarizing RMS TDRS orbit differences (GET vs. BRTS). The first three solutions correspond to TDRS-3 and the last to TDRS-5.

A covariance study was performed at JPL to calculate anticipated performance of a small (100-km) size GET network. The covariance study agrees well with actual field test results discussed earlier. The covariance study focused on dependence of geosynchronous orbit accuracy **on** the **quality** of **the small amount** of the **two-way** range **data** which were combined with the **GET data.** Figure **9 shows this calculated dependence.** An alternate approach, which could eliminate the need for this small amount of two-way range data, would be to deploy a copy of the 3-station 100-km size network on the opposite coast of the United States. In this case, differential one-way range from the stations separated by several thousand km could constrain the 6th orbital clement.

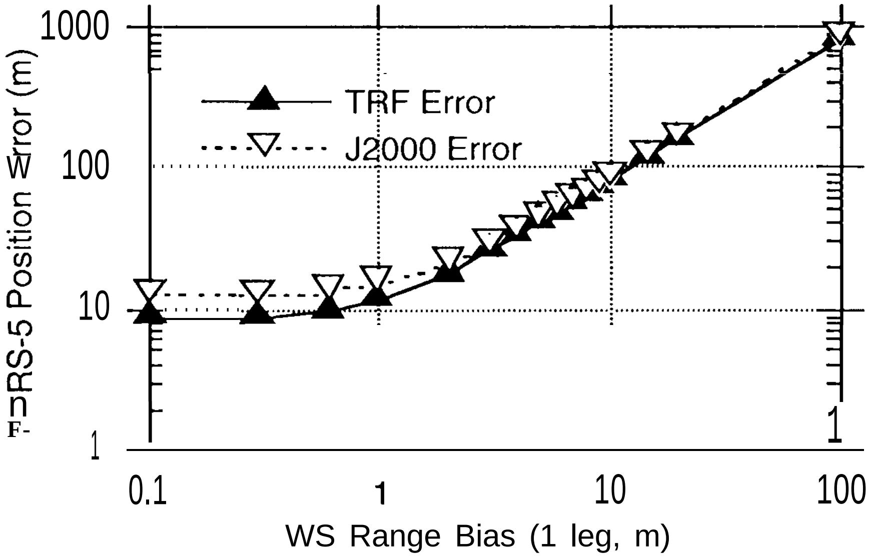


Figure 9. Expected total position error for TDRS-5 (1 σ) as a function of the one-leg WSC range bias for 100 km network from covariance analysis. The orbit error is given in both the inertial (J2000) and terrestrial reference frames (TRF).

Down-looking GPS Tracking

For down-looking GPS tracking, the geosynchronous (or high-altitude) satellite carries a GPS receiver. The GPS constellation illuminates the Earth from an altitude of 20,200 km and as such, is better suited for low-Earth users. Since the geosynchronous spacecraft are located above the GPS constellation, they must look down to receive GPS signals spilled over the limb of the Earth from satellites on the other side of the planet (down-looking GPS tracking, Figure 1). The number of useful GPS spacecraft is limited to those that fall within an annular region delineated on the inside by the Earth blockage and on the outside by the beamwidth of the GPS signals. On average, the signals from only 1-2 GPS satellites can be seen from geosynchronous altitude at any given time under the viewing assumptions described above. Of course this entirely precludes the possibility of kinematic positioning, which requires four GPS in view, and the orbits must be determined dynamically. Even if sidelobe signals from GPS can be tracked (Ref. 11), the number of GPS in view, while larger, still is less than four most of the time. For a spacecraft at geosynchronous altitude, however, the perturbative accelerations due to the non-spherical Earth are highly attenuated and the effects of atmospheric drag are negligible. As a result, the proper modeling of the forces acting on a spacecraft is much less problematic than it is for a low-Earth orbiter.

There are certainly significant advantages to navigation based on a flight GPS receiver for a geosynchronous satellite. These include potential for autonomous navigation and the capability to, in principle, perform orbit determination and plan and execute maneuvers without any ground-based input or activity. This could have significant strategic and cost-saving advantages. On the other hand, certain GPS system errors are magnified by the non-optimal viewing geometry from high altitude orbit.

We have evaluated the down-looking GPS tracking scenario with the assumption that no ground-based tracking data with the geosynchronous orbiter would be incorporated into the orbit determination process; it would be based totally on GPS tracking from the orbiting receiver. In our nominal case, wc assumed that the GPS flight receiver onboard the geosynchronous orbiter would be a Y-code capable receiver; that is, it would not be affected by selective availability and it could track at both L 1 and L2 frequencies. In a second case study, wc assumed a commercial receiver without Y-code capability, but still with the dual-frequency capability. Dual-frequency space GPS receivers are commercially available from several vendors. These receivers, which are in widespread use at ground sites, use a code-free technique to recover L 1 and L2 phase and pseudorange data, while still not using information from the encrypted Y-code. The assumptions of the down-looking analysis are described more fully in Ref. 8, and are summarized in Table 1. The use of "consider parameters" refers to parameters whose values are not estimated in the covariance study, but are instead calculated from the geometry and their partial derivatives, and thus are treated as sources of systematic error for the orbit determination of the spacecraft. One error source is notably missing: because we assumed dual-frequency receivers, we include no contribution from the ionosphere. If a single-frequency receiver were used, there would be a sizable effect from ionosphere path delay due to the Earth-grazing type of measurement geometry. In fact, the total delay from the ionosphere in this configuration can approach six times the zenith delay as seen from the Earth. Zenith delays at Earth arc roughly between 3 meters and 15 meters depending on the solar cycle, although higher delays are sometimes experienced. This would result in systematic measurement errors which, for **a single frequency receiver at** geosynchronous altitude, could range from 18 to 90 meters, which is significant when compared to the performances shown in the covariance studies below. With a L 1 -only receiver, one expects that the ionosphere error would contribute significantly to the overall error budget.

Table 1
ERROR MODELS FOR DOWN-LOOKING GPS

A PRIORI FOR ESTIMATED PARAMETERS				
TDRS Position (X, Y, Z)	10	km		
TDRS Velocity (X, Y, Z)	1	m/s		
TDRS Clock Bias	33	μsec		
TDRS Clock Drift	3	nsec/s		
CONSIDERED PARAMETERS				
	Y-code	receiver	Non-Y-code	receiver
TDRS Solar Radiation Pressure	5	%	5	%
GPS Position (RSS 3-d)	7	m	30	m
GPS Clock Error	6	nsec	60	nsec
Earth GM	2	ppb	2	ppb

Figure 10 shows anticipated orbit accuracy for a geosynchronous orbiter (in this case, one of the TDRS satellites) with down-looking GPS tracking. The two cases shown correspond to users with and without access to the Y-code (with decryption and without decryption). The fit is performed over a 24-hr arc. The errors shown at t=24 hrs correspond to accuracy available in real-time. Figure 11 breaks down the total error into components averaged over the 24-hr interval. Note that the overall error is about 60 meters for the user without Y-code decryption, but a Y-code user can obtain about 6-meter 3-D (RSS) accuracy. Figure 12 shows the recovery of the full state after a maneuver, assuming that all state parameters must be redetermined as if from a cold start. In practice, it should generally be possible to model the maneuver and estimate parameters to characterize it, which can significantly reduce the number of degrees of freedom in the ephemeris solution. Therefore, Figure 12 may be somewhat pessimistic, and quicker recovery should be possible.

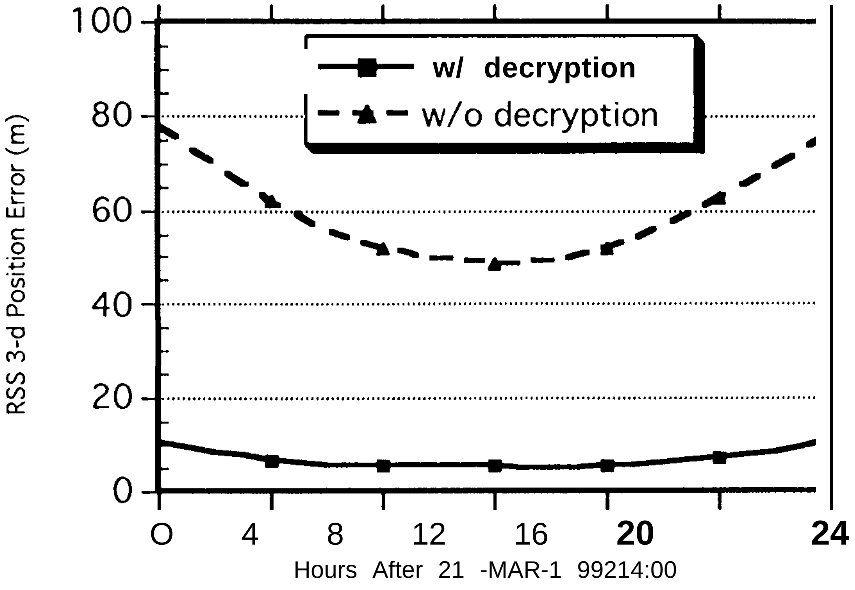


Fig 10. TDRS-W position error for 24-hour arc. Orbit determined using down-looking technique.

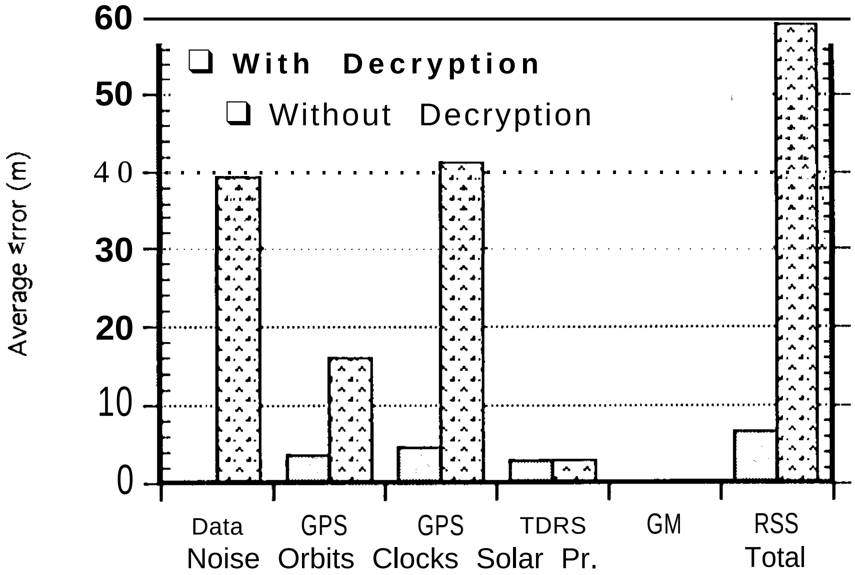


Fig 11. TDRS-W position error for 24-hour arc. Orbit determined using down-looking technique.

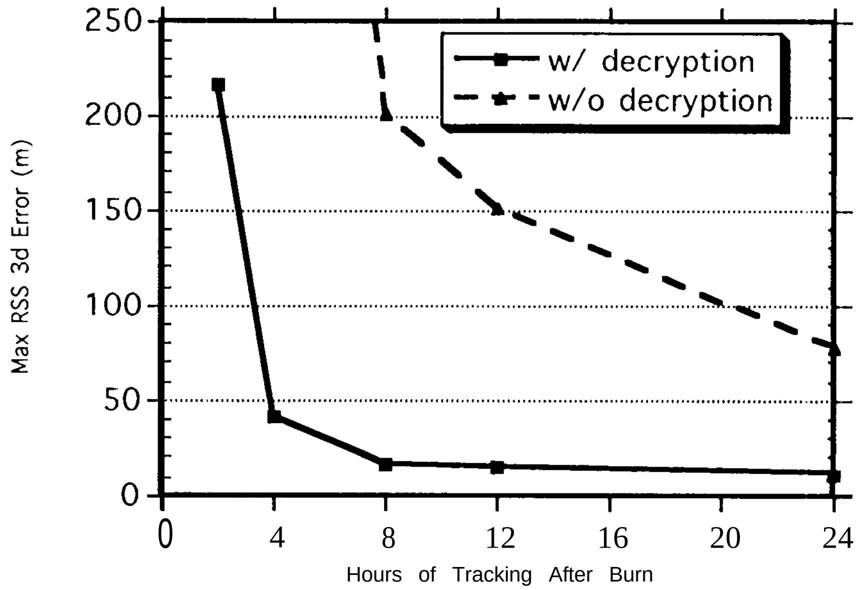


Fig 12. TDRS-W maximum position error after station-keeping maneuver for down-looking technique. Orbit after maneuver is determined using full TDRS-W orbit state recovery.

Future Work: microGPS Experiment on STRV-1C

Two space missions are scheduled in the near future to carry a new type of GPS flight instrument called a microGPS receiver (Figure 13). The microGPS receiver (Refs. 9, 10) is also known as the "bit grabber" GPS space receiver (13 GGSR), consisting of a GPS patch antenna, an inexpensive oscillator, a signal sampler/downconverter, and a memory chip. Such a receiver will not only fulfill stringent power (<0.1 W) and mass (<1 kg) constraints, but with the inclusion of an onboard processor could potentially offer autonomous tracking capability. The microGPS requires very low power because it awakes from a "sleep" mode only occasionally to sample GPS signals for a short duration (- several millisec).

The first BGGSR space mission is the NASA-funded SNOE (Student Nitric Oxide Explorer), to be launched into a 550-km circular orbit in October, 1997. The BGGSR experiment goal is to demonstrate 200-m orbit determination accuracy. The second is the STRV-1C (Space Technology Research Vehicle) mission, to be launched in early 1999 by DERA. It will have a highly elliptical orbit with a goal to characterize GPS signal strength from 300 km to geosynchronous orbit altitudes. JPL is providing the microGPS flight instrument to STRV- lC, in collaboration with the DERA in the United Kingdom. The STRV-1C microGPS experiment is a joint effort of DERA, the U.S. Department of Defense (DOD), and NASA.

The microGPS instrument BGGSR has three notable applications for List in space environments:

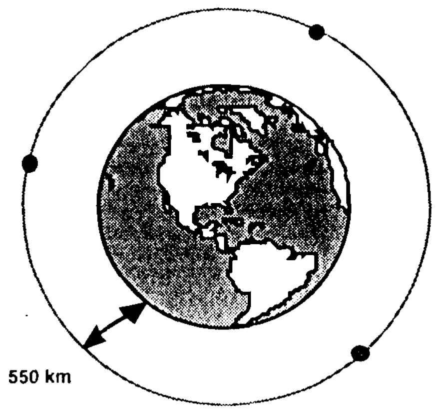
1) Real-time, **near-real time, or post-fit orbit determination for a low-Earth** orbiter while requiring only very small amounts of onboard power (O. 1 watt) and mass (< 1 kg), at a cost only a small fraction of conventional GPS receivers. Due to the design simplicity and small number of parts, space reliability can be high.

2) Providing a front end to a more sophisticated GPS flight receiver. Development of such an advanced GPS receiver is currently underway at JPL.

3) Sampling raw GPS signals at minimal cost in environments where signal characteristics may be variable or unusual, so that new in-receiver software or firmware can be developed to accommodate the different tracking conditions.

The microGPS experiment on STRV- 1 C is primarily oriented to the third application listed above. For SNOE, the first application is the primary motivation. For STRV- 1 C, the intention is to sample the GPS broadcast signals over a wide range of altitudes (low-Earth to geosynchronous) to confirm that the GPS signals can be tracked over this range, characterize the power, polarization, and other aspects of the GPS transmissions over the entire altitude range, and verify that it is possible to track enough GPS satellites at geosynchronous and other high-Earth altitudes with a flight GPS receiver to provide a full navigation capability for spacecraft. The STRV-1C microGPS experiment will also test the viability of tracking GPS sidelobe signals for use in orbit determination, as well as the down-looking tracking approach for GPS-based navigation. In the course of analysis of the STRV- 1 C microGPS data, the impact of the onboard clock's stability on system performance will also be assessed.

A very simple check on the link budget for tracking GPS down-looking from geosynchronous orbit can be done through analogy with ground-based GPS tracking. Consider the loss in power due to receiving the signal at geosynchronous orbit at 20 degrees from the GPS boresight, instead of the O degrees from boresight which might be anticipated from a ground receiver: the loss is -13 dB, based on the GPS transmit beam pattern. For the space loss relative to ground reception, $(26{,}000/68{,}000)^2 = 0.15$ or -8.3 dB. Relative to a typical geodetic ground antenna, we assume -2 dB loss from the receiver antenna gain. These accumulate to -23.2 dB, or 0.0048. For a typical ground receiver tracking CA code, we expect signal/noise ratio (SNRv) of - 600 in l see, or $(600)\,x(0.0048)^{0.5} = 41.5$ for the down-looking geosynchronous case, or SNRV of 4.15 for a 10 millisec sample. Based on these order of magnitude estimates, we expect to be able to sample and detect the GPS signals at geosynchronous altitude with the microGPS bit-grabber samples of at least 10 msec duration. A more detailed link analysis is presented in Ref. 11, in which it is shown that with longer samples (> 100 msec), it should be possible to detect at least some of the sidelobe GPS signals.



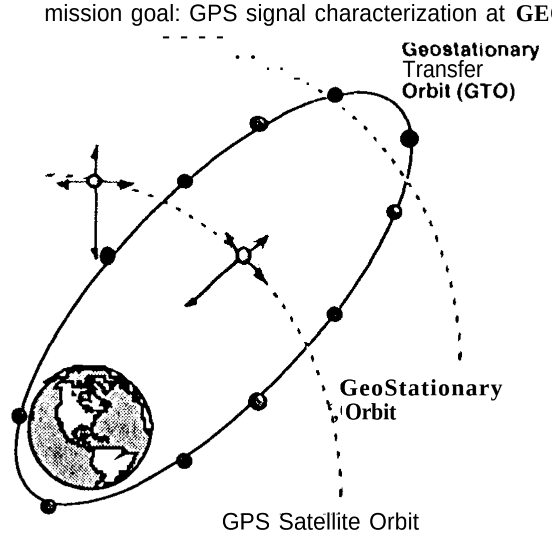


Fig 13. SNOE and STRV-1C missions will each carry a flight microGPS receiver

Determination of the number of GPS visible as a function of orbiter altitude and characterization of the signal strength is one of the key goals of the STRV-1C GPS experiment. Such data are critical to understanding the capability for exploiting GPS for positioning and navigation at higher altitudes. If fewer than 4 GPS are visible most of the time, then some fundamental changes will have to be made to most current GPS receivers for them to be usable at high altitudes: most receivers require that at least 4 GPS be visible to initialize and perform acquisition and tracking functions. As discussed in Ref. 11, four (or more) GPS satellites may be visible at high altitude depending on the ability to acquire and utilize sidelobe data. For geostationary or geostationary transfer orbits, it may only be necessary to be able to track 4 GPS satellites at some point in the orbit or trajectory in order to initialize the receiver and obtain the GPS broadcast ephemeris; from then on, even though fewer than 4 GPS may be in view at any given time, the orbit estimator can use the dynamic fitting techniques used in the above studies (Figures 10-12) to continuously maintain the knowledge of the satellite orbit.

Figures 10-11 show anticipated orbit accuracy under certain assumptions for the case where only 1-2 GPS satellites are visible at a time (on average) in the down-looking geometry. In the near future, we plan to evaluate the possible ranges of accuracies for a larger number of GPS in view based on the possible tracking of sidelobe GPS signals. These assessments will be done through simulations and covariance studies, One possible enhancement would be to make the GPS receiver on the geostationary satellite be capable of tracking the GPS cross-link signals which will be implemented on future GPS satellites (Block IIR and beyond). In the extreme case, we would assume that a future embodiment of the GPS constellation would include a zenith transmit antenna, broadcasting GPS data up to satellites in geostationary orbits (and beyond). In that case, about 13 GPS satellites could be tracked simultaneously by a receiver on a geostationary satellite, and based on very simple dilution of precision geometrical arguments, one could argue that real-time point positioning would be possible (with a Y-code receiver) at the -10-meter level, and with dynamic fitting and filtering, the orbit accuracy could improve to better than 1 meter (these numbers would degrade by a factor of 5-10 for receivers affected by selective availability). If, additionally, cross-links between multiple geostationary satellites were incorporated, as might be possible in a cooperative constellation, further accuracy improvement for both real-time and post-fit solutions would be achievable.

The STRV-1C mission will provide the essential data needed to begin to evaluate these possibilities. Through analysis of the data from the JPL microGPS bit-grabber, we expect to be able to characterize the utility of GPS radiometric data for positioning and navigation over an altitude range of up to geostationary altitude. These data can then be the "basis for planning future missions and design of GPS flight receivers intended for operation at higher altitudes.

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